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Modelling for Roof Failure Analysis in an Underground Cave

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***Abstract*—**Roof collapse is one of the problems with a higher frequency in most of the mines of all countries, even now. There are many reasons that may cause the roof to collapse, namely the mine stress activities in the mining process, the lack of vigilance and carelessness or the complexity of the geological structure and irregular operations. This work is the result of the analysis of one accident produced in the "Mary" coal exploitation located in northern Spain. In this accident, the roof of a crossroad of excavated galleries to exploit the "Morena" Layer, 700 m deep, collapsed. In the paper, the work done by the forensic team to determine the causes of the incident, its conclusions and recommendations are collected. Initially, the available documentation (geology, geotechnics, mining, etc.) and accident area were reviewed. After that, laboratory and on-site tests were carried out to characterize the behaviour of the rock materials and the support used (metal frames and shotcrete). With this information, different hypotheses of failure were simulated to find the one that best fits reality. For this work, the software of finite differences in three dimensions, FLAC 3D, was employed. The results of the study confirmed that the detachment was originated as a consequence of one sliding in the layer wall, due to the large roof span present in the place of the accident, and probably triggered as a consequence of the existence of a protection pillar insufficient. The results allowed to establish some corrective measures avoiding future risks. For example, the dimensions of the protection zones that must be remained unexploited and their interaction with the crossing areas between galleries, or the use of more adequate supports for these conditions, in which the significant deformations may discourage the use of rigid supports such as shotcrete. At last, a grid of seismic control was proposed as a predictive system. Its efficiency was tested along the investigation period employing three control equipment that detected new incidents (although smaller) in other similar areas of the mine. These new incidents show that the use of explosives produces vibrations which are a new risk factor to analyse in a next future.

***Keywords*—**Forensic analysis, hypothesis modelling, roof failure, seismic monitoring.

I. INTRODUCTION

ROOF collapse is an important problem in mining industry all over the world. In China, roof collapse accounts for 55% of all mine accidents [1]. In January of 2020 a roof collapse occurred at the Moranbah North underground mine in the Bowen Basin, northern Queensland and although it has not produced injuries, the mine had to be closed to ensure the security [2].

This work is the failure analysis of a roof incident in a coal mine in northern Spain and its principal scope is to establish the causes of the accident to improve the security in other mining areas of this exploitation. The followed methodology begins with field works to recognize the area and to characterize geological materials. Then, different hypotheses were developed and a computational simulation was used to evaluate their viability.

Till 2009, the deposit was exploited through a mountain mine methodology (levels between 1050 and 1650 m). From that year, a ramp to access the deepest areas was built (levels between 1050 m and 800 m). This ramp has a total length of 214 m, with a downward slope of 12%. The width of the tunnel is 10 m and the height in the centre of the crown is 6.8 m, presenting a free transversal section of 50 m^2. It goes through very different lithologies. These lithologies can be grouped in three categories whose properties are summarized in Table I.

TABLE I
GEOTECHNICAL CHARACTERISTICS OF THE LITHOLOGIES

Name	Lithology	RQD	RMR
Section A	Fractured sandstone and coal	25/60	21/40
Section B	Sandstone/Shale	50/75	41/60
Section C	Sandstone	75/90	61/80

Different supports have been designed for each group of lithologies. The group with poor quality (Section A) has been reinforced more than the best one (Section C). In Table II the support for each group is shown. Although in it, the coal has not taken into account, it should be similar (because of its Rock Mass Rating or RMR) [3] to the Section A. From the ramp, there are infrastructure galleries giving access to transversal galleries and guide galleries. It was in one of the guide galleries where the incident occurred as a result of a roof collapse. The tailgate is named "Morena Oeste" and has a height of 853 m.

TABLE II
EMPLOYED SUPPORT

Section	Advance (m)	Shotcrete (cm)	Bolts (m^2)	Steel rib
A	1-2	20	1.00	SI
B	2-3	15	1.00	NO
C	3-4	10	2.25	NO

In this paper, the study carried out to define the causes of the accident is described.

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II. RECOGNITION WORKS

A. Recognition of Ramp and Place of the Accident

Along the ramp, when coal layers are crossed, the shotcrete support suffers a lot, because when this type of ground is deformed, it cracks and detaches the shotcrete. At some points it was found that the thickness of shotcrete was small and, in others, the shotcrete was not resting on the floor, if not "hung". These situations indicate that the shotcrete was not working properly as support. On the other hand, the infiltrating water produced oxidation problems in the bolts, as well as in the reinforcing fibbers of the shotcrete in the sections they were metallic. These problems are shown in Fig. 1. In some places, the support was reinforced by increasing the bolt density or installing new wood-clad metal frames (Fig. 2).

As indicated above, the accident occurred in the called "Morena Oeste". This gallery with a height of 853 m has a cross section of 6 m of width and 5.2 m of height, with the exception of the collapsed area where the section increases to 10 m of width and 7 m of height. This bigger size allows creating a transference place where the coal is loaded and evacuated to the outside.

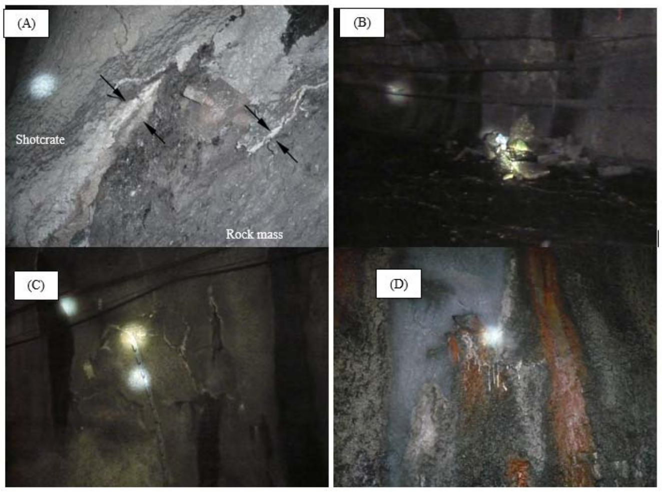

Fig. 1 Found problems in the shotcrete: (A) poor thickness, (B) detached blocks, (C) cracking, (D) leaks and oxidation

Fig. 2 Places with reinforced support in the ramp

The area of the collapse was entirely reinforced after the incident, with new metallic frames (type Th29) and a coating of wood that in some areas exceeded one meter of thickness (see Fig. 3). The coating wood produces a reduction of the size of the section. On the right wall, where the detachment of material happened, the metal frames were braced by embedding them in a concrete wall.

Fig. 3 Reinforced support after the accident

B. Geotechnical Characterization of the Ground

In this area the power of the coal layer ranges between 1.5 and 1.8 m, it has a dip of 40 to 47º and the length of the exploitation workshops is 140 m, although there is a protection mass of about 50 m high.

The roof material is a very quality sandstone, while in the walls there are alternations between shales and sandstones. In laboratory, with samples of these materials, different tests were done: uniaxial strength, indirect tensile strength and triaxial compressive strength. From these tests, the parameters of the Mohr-Coulomb curve were obtained (see Table III) [4].

TABLE III
PROPERTIES OF THE ROCK

Lithology	Uniaxial strength (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Friction (º)
Roof	155	14.5	30.7	53.9
Wall	108	6.3	16.1	53.5

Once the rock values were obtained, it is necessary to calculate the strength and deformation parameters of the rock mass, assigning the RMR values collected in Table II [4]. The results are shown in Table IV.

TABLE IV
PROPERTIES OF THE ROCK MASS

Material	Cohesion (MPa)	Friction (˚)	Elastic module (GPa)
Roof	4,9	46	50
Layer	0,2	25	3
Wall	1,7	32	18

III. FORENSIC ANALYSIS OF THE CAUSES OF THE ACCIDENT

After analysing all the sliding planes and recognizing the incident place and its surroundings, it is unlikely that the detachment that originated the accident could be attributed to the fall of a roof wedge or a coastal wedge. The main working hypothesis is that this collapse was due to a sliding of strata in favour of the slope. To confirm this hypothesis, a computer simulation was carried out. Its characteristics are described below.

A. Computer Simulation

By mean of the software FLAC 3D [5], a tridimensional model was generated that reproduces the conditions of the exploitation in the place where the incident happened.

The model shown in Fig. 4 has 350 m width and 270 m height. The rest of the ground, until reaching the 700 m depth, was replaced by an equivalent overload. In the figure, it is possible to see the different simulated materials: the layer of coal (in green), the roof of the layer (sandstones, in blue), the wall of the layer (shales, in red), and the simulated works of the exploitation: the tailgate and the workshop of the exploitation with the protection pillar between them.

Once the tensions were initialized, the excavation of the tailgate with its support (metal frames type TH29 per metre and 10 cm of shotcrete) and the exploitation of the workshop were simulated. The support was simulated by mean of beam elements. Three different cases were simulated:

1) Case 1: The tailgate has the most common dimensions in this type of infrastructure, that is to say, 6 m of width and 5.2 m of height.
2) Case 2: The tailgate has a bigger cross section, 10 m of width and 7 m of height. These dimensions are the dimensions of the collapsed place (Fig. 5).

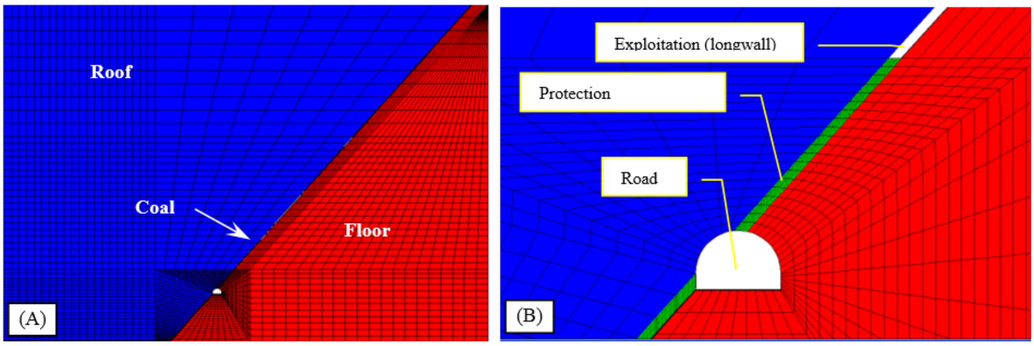

Fig. 4 Model description

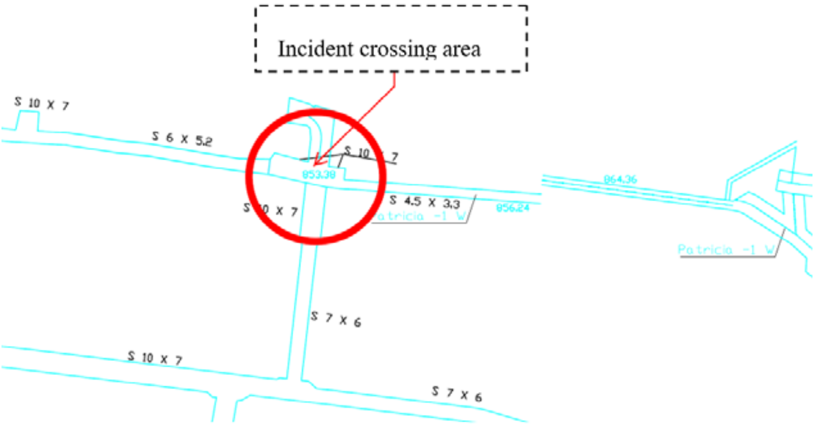

Fig. 5 Dimensions of the galleries in the collapsed area

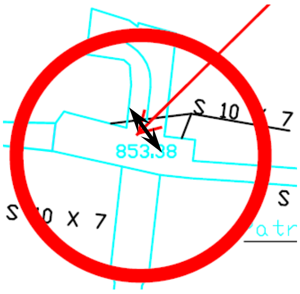

Fig. 6 Equivalent diagonal dimension

3) Case 3: As in the collapsed place there was a dugout, it has considered other case with the dimensions of the diagonal cross of this place, that is to say 14 m (Fig. 6).

The results obtained in each case are described and analysed below

B. Case 1: Tailgate 6 m x 5.2 m

Fig. 7 shows the vertical displacements (in meters) of the model around the gallery. They are represented in the form of isovalues, so each colour is equivalent to an interval of displacements according to the legend that appears on each figure. They are negative when their direction is descending and positive when their direction is ascending (swellings).

The simulation shows displacements of 3 cm in the roof and swellings of 1 cm in the floor. These displacements increase to 9 cm and 2 cm respectively after the longwall exploitation.

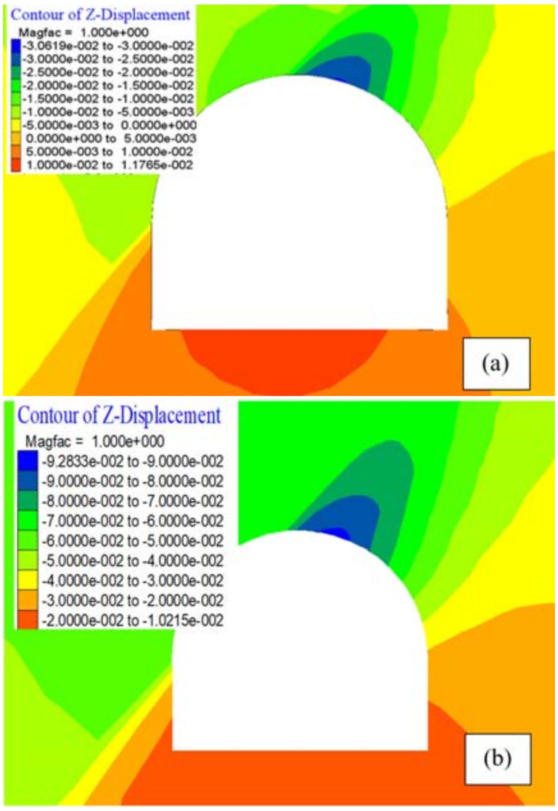

Fig. 7 Vertical displacements: (a) during tailgate opening;(b) during longwall exploitation

Fig. 8 shows the axial efforts over the support. The efforts go from 20 t before the exploitation until 50 t after the exploitation. In this figure, the geometric deformation of the gallery is represented in a magnified way. It can be noticed that in the intersection with the coal layer the deformation is bigger and this change in the deformation produces cracks in the shotcrete. In this case, less rigid and more flexible supports, as wood, have a better behaviour because they better absorb the deformations.

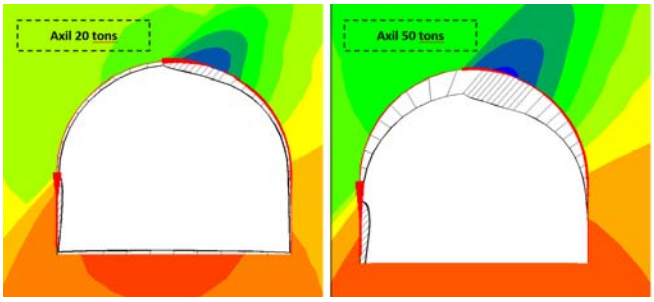

Fig. 8 Axial efforts over the support and tailgate deformation before and after the exploitation

C. Case 2: Tailgate 10 m x 7 m

The bigger dimensions of the cross section produce an increase in the vertical displacements until 4 cm. Besides, a plasticized zone around the tailgate appears not only along the exploitation but also before it (Fig. 9).

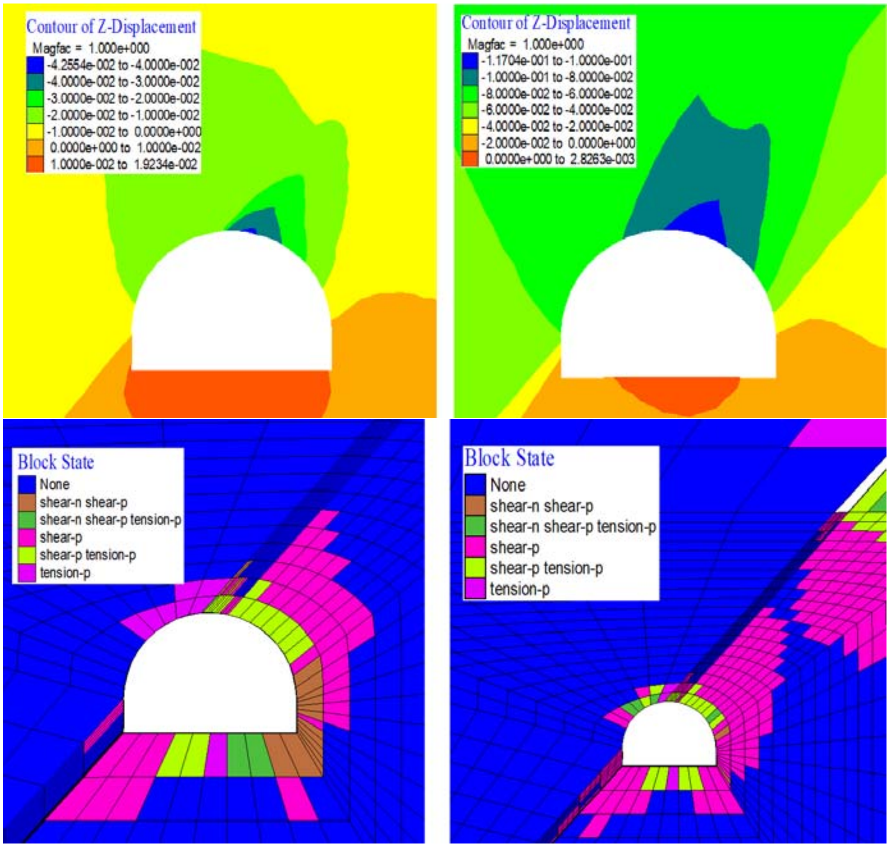

Fig. 9 Vertical displacements and failure surrounding of the tailgate before and after the exploitation

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Again, a change in the deformation appears in the intersection with the coal layer affecting the integrity of the shotcrete and producing cracks and detachments. The axial effort reaches the 24 t bigger than in the first case with one effort of 20 t.

After the exploitation, the displacements and the fractured surrounding increase in an important way and the support is overloaded until 60 t.

D. Case 3: Diagonal 14 m

When the dimension of the tailgate is equivalent to the diagonal (14 m), the vertical displacements in the roof reach 5.5 cm and in the floor 2.5 cm. Again, is the wall of the layer the most affected placed with an increase in the fracturing and failure (Fig. 10).

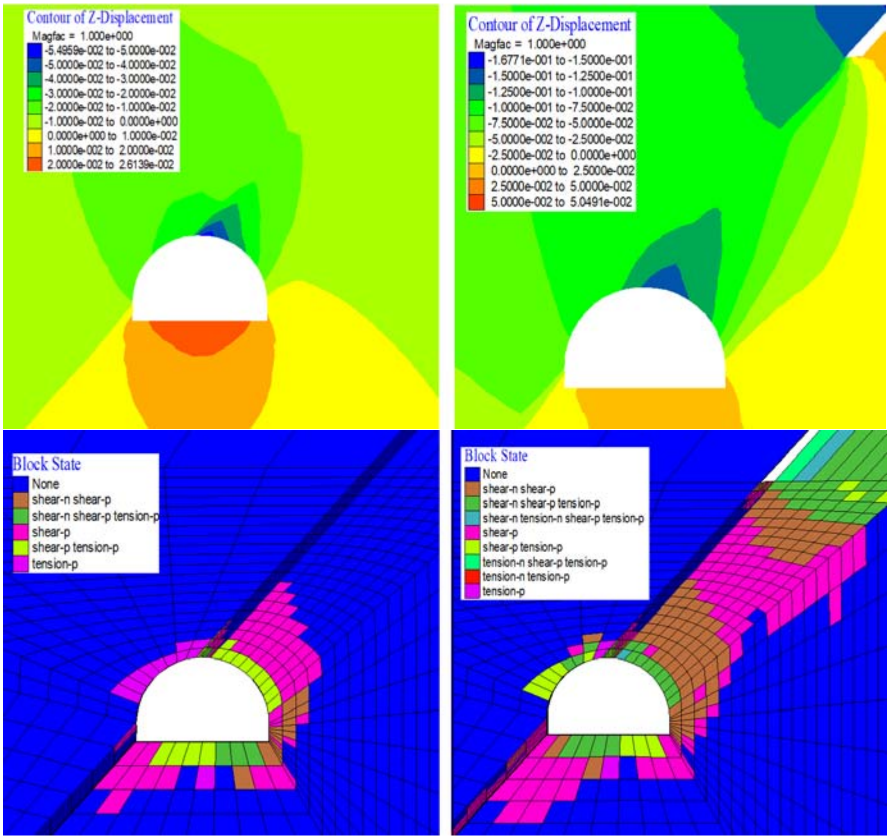

Fig. 10 Vertical displacements and failure surrounding of the tailgate, before and after the exploitation for 14 m of diagonal

Once the workshop is exploited, the vertical displacements in the roof reach 15 cm, while the wall of the layer is totally plasticized between the tailgate and the workshop. There are very significant zones in the figure with a tendency to the break and/or landslide. This indicates that, if a landslide starts, it will take place in the wall of the layer and that the volume of involved material will be considerable, since the affected area has considerable grown compared to the previous situations.

IV. CONFIRMATION OF THE WORK HYPOTHESIS

The simulated cases allow clarifying three fundamental things:

Firstly, it has been found that, in all cases, the fractured area mainly affects the wall of the layer and hardly the roof or the layer itself. Therefore, it is in this area where the collapse begins and, therefore, it is necessary to reinforce in those places where similar situations occur.

Secondly, it is necessary to notice that the greatest damage is generated in case 3, where it can be seen that both the crown and the gallery shoulder located in the wall area are subject to shear, indicating a tendency to slide. Besides, how the damaged area around the tailgate is connected with de damaged area around the exploitation workshop, if the movement starts, a global breakage will occur. This breakage could reach the workshop, so it would be impossible to contain with the support.

Finally, it has been verified that the redistribution of stresses that occurs in the rock mass as a consequence of the exploitation of the workshop supposes one increase in the deformations around the tailgate, even communicating the plasticizing areas of the workshop and the gallery. Therefore, the dimensions of the protection pillars must be reconsidered in order to minimize this effect. With this end, two new tests with an increase in the height of the protection mass to 70 and 80 m have been made.

Protection pillars of 70 m could be suitable for gallery widths of up to 10 m (see Fig. 11), but they are insufficient when considering a gallery dimension equivalent to the diagonal (14 m) because in this case, the plasticizing areas around the tailgate and the exploitation workshop appear again. On the other hand, with 80 m protection pillars, the plasticizing areas around the exploitation workshop and the tailgate are not connected (Fig. 12). Therefore, in case of one slide, it would be a local break in which the volume of material that can fall is much less and the support would behave better. Based on these observations, it seems to be confirmed that the detachment was originated as a consequence of one sliding in the layer wall, due to the large roof span present in the place of the accident, and probably triggered as a consequence of the existence of a protection pillar insufficient.

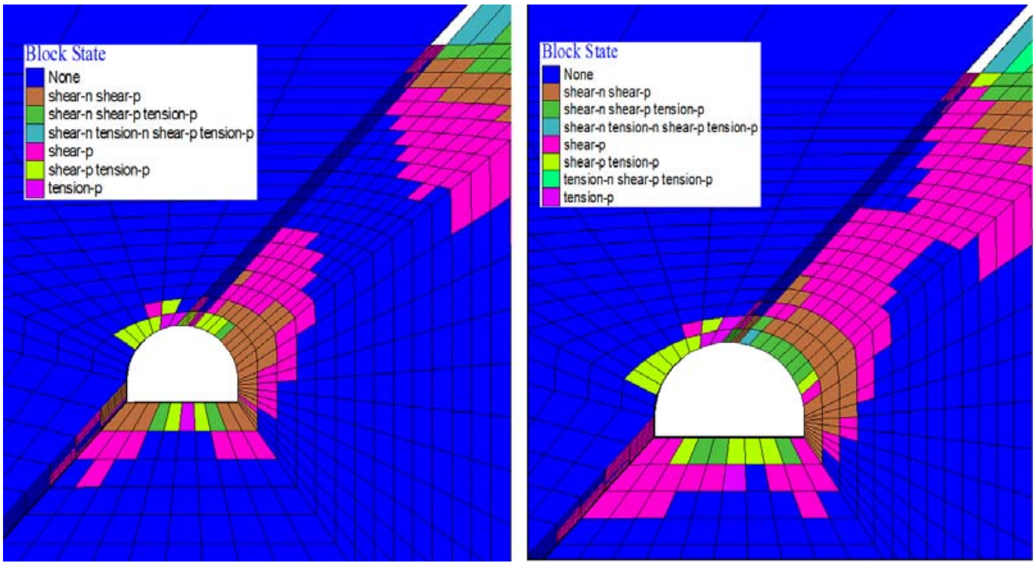

Fig. 11 Failure surrounding after the exploitation for 10 and 14 m and with protection pillar of 70 m

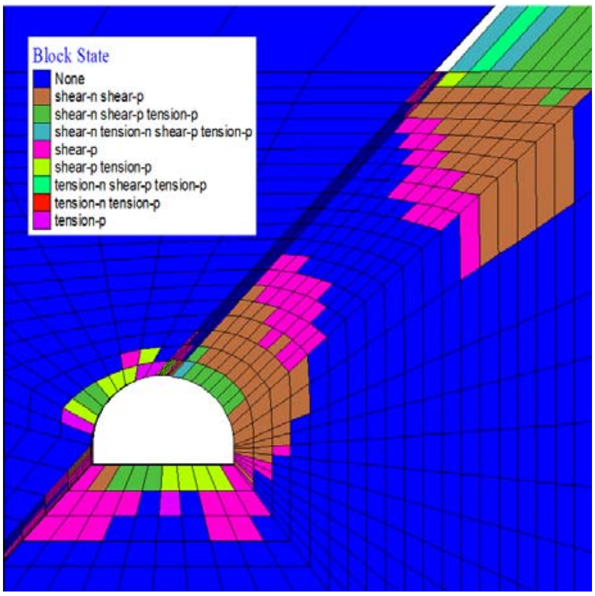

Fig. 12 Failure surrounding after the exploitation for 14 m and with protection pillar of 80 m

V. CONCLUSIONS

The main conclusions derived from the study are presented below.

1) The area where the incident occurred (Morena Layer) is characterized by two circumstances:
   - It is a cross between two large sections, 10 m of width and 7 m of height (when the usual is 6 m of width and 5.2 m of height). If the effect of the cross is also taken into account, there is an equivalent width of 14 m, corresponding to the diagonal.
   - In this area a protection pillar was left in the untapped workshop of triangular geometry and with about 50 m of height.
2) The roof of the layer is made up of very resistant sandstones (puddles) (more than 100 MPa at simple compression). Besides they are very little fractured, with a very high RMR, around 80. The wall, however, is composed of slates (alternating with sandy levels), with a lower RMR.
3) The recognition around the place of the incident shows evidences that the elements of the supports were overloaded due to the thrust of the ground producing breaks, detachments of the shotcrete, deformed steel frames and slipped staples.
4) The computer simulations with the software of finite differences FLAC 3D reveal the following aspects:
   - While the exploitation of the workshop does not take place, the tailgate does not suffer excessively (do not mind the simulated dimensions).
   - It is the wall of the layer that undergoes the main fracture processes (failure). These processes are very local in the floor.
   - One increase in the dimensions of the gallery (from 6 m to 10 and 14 m) produces one increase in the affected area.
   - Once the workshop is exploited, the response of the

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surrounding of the tailgate is very different. This response is function of the width of the tailgate and the dimensions of the protection mass.

– When the simulated width of the gallery is 6 m, the fractured area in the wall around the gallery and around the workshop remains completely isolated and independent.
– When the simulated width of the gallery is 10 m, the fractured (plasticized) areas on the wall around the gallery and around the workshop approach until almost touching.
– When the simulated width of the gallery is 14 m (the diagonal), the fractured (plasticized) areas on the wall around the gallery and around the workshop join. In addition, areas subjected to shear appear indicating a tendency to slide.

5) Based on these observations, it seems to be confirmed that the detachment was originated as a consequence of one sliding in the layer wall, due to the large roof span present in the place of the incident, and probably triggered as a consequence of the existence of a protection pillar insufficient for isolating the gallery from the plasticized produced in the nearest exploitation workshop.

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